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Excitation Energy as a Basic Variable to Control Nuclear Disassembly

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Thermodynamical features of Xe system is investigated as functions of temperature and freeze-out density in the frame of lattice gas model. The calculation shows different temperature dependence of physical observables at different freeze-out density. In this case, the critical temperature when the phase transition takes place depends on the freeze-out density. However, a unique critical excitation energy reveals regardless of freeze-out density when the excitation energy is used as a variable insteading of temperature. Moreover, the different behavior of other physical observables with temperature due to different ρ_f vanishes when excitation energy replaces temperature. It indicates that the excitation energy can be seen as a more basic quantity to control nuclear disassembly.

The phase transition and critical phenomenon of small systems is an interesting subject in recent nuclear physics research. The break-up of nuclei due to violent collisions into several intermediate mass fragments (IMF), can be viewed as critical phenomenon as observed in fluid, atomic, and other systems. It prompts the possible signature on the liquid gas phase transition of the nuclear system. On one hand, the onset of the multifragmentation [1] and vaporization [2] channels can be seen as the signature of the boundaries of phase mixture [3]. This is supported further by the fact that the caloric curve in a certain excitation energy range [4] shows a saturate similar to a first order phase transition, in the framework of statistical equilibrium models [5]. On other hand, the observation of critical exponents parameters in the charged or mass distribution of the multifragmentation system [6] can be interpreted as an evidence of the phase transition. Recently, the lattice gas model (LGM) has been applied to treat phase transition and critical phenomenon in the nuclear disassembly for isospin symmetrical [7] and asymmetrical [8,9] nuclear systems. LGM assumes a freeze-out density ρ_f with thermal equilibrium at temperature T. The temperature was adopted naturally as a variable to study the feature of disassembly in nearly all previous calculation of LGM. In this paper, we will illustrate that the excitation energy can be taken as a more basic quantity to control the disassembly of nuclear system rather than temperature via studying the features of critical phenomenon and other physical observables in the lattice gas model.

In the lattice gas model, A nucleons with an occupation number s which is defined as $s = 1$ (-1) for a proton (neutron) or $s = 0$ for a vacancy, are placed in the L sites of lattice. Nucleons in the nearest neighbouring sites have interaction with an energy $\epsilon_{s_is_j}$. The hamiltonian is written by $E = \sum_{i=1}^{A} \frac{P_i^2}{2m} - \sum_{i<j} \epsilon_{s_is_j} s_i s_j$. The interaction constant $\epsilon_{s_is_j}$ is related to the binding energy of the nuclei. Here $\epsilon_{nn,pp} = \epsilon_{-1-1,11} = 0$ MeV, $\epsilon_{pn,np} = \epsilon_{1-1,-11} =$ -5.33 MeV is used. The freeze-out density of disassembling system is $\rho_f = \frac{A}{L}\rho_0$ where ρ_0 is the normal nucleon density. The disassembly of the system is to be calulated at ρ_f, beyond which nucleons are too far apart to interact. $N + Z$ nucleons are put in L cubes with size l^3 by Monte Carlo sampling using the Metropolis algorithm. Once the nucleons have been placed, their momentum is generated by a Monte Carlo sampling of Maxwell Boltzmann distribution. Various observables can be calculated in a straightforward fashion.

One of the basic measurable quantities is the distribution of fragment mass. In this LGM, two neighboring nucleons are viewed to be in the same fragment if their relative kinetic energy is insufficient to overcome the attractive bond: $P_r^2/2\mu + \epsilon_{np} < 0$. Once the fragment mass distribution is built, we can extract the effective power law parameters via fitting the mass distribution of fragments with $Y(A_i) \propto A_i^{-\tau}$ and its second moment of fragment distribution defined

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as [10] $S2 = \frac{\sum_{i \neq A_{max}} A_i^2 * n_i(A_i)}{A}$, where $n_i(A_i)$ is the number of fragments with A_i nucleons and the sum excludes the largest cluster A_{max}. There are a minimum of τ and a maximum of S2 at critical point for an infinite system. Besides the above quantities, we will use the average multiplicity $< IMF >$ of IMF and the information entropy H to search the critical point [11,12]. H was defined firstly by Shannon in information theory [13] and can be introduced into nuclear dissociation [12], it reads $H = -\sum_i p_i * ln(p_i)$, where p_i is the probability having "i" produced particles in each event, the sum is taken over all multiplicities of products from the disassembling system. H reflects the capacity of the information or the extent of disorder.

We choose the medium size nuclei ^{129}Xe as an example to analyze the nuclear disassembly. Three freeze-out densities of $0.18\rho_0$, $0.38\rho_0$, and $0.60\rho_0$, corresponding to the lattice size of 9^3, 7^3 and 6^3 respectively , were used. The calculations were performed from 3 MeV to 7 MeV and 1000 events were accumulated at each temperature and freeze-out density.

We show the temperature and freeze-out density dependences of τ, $< IMF >$, H and $S2$ in the left columu of Fig.1. First, the critical temperatures determined by the extreme values are the same for the same freeze-out density, indicating that critical phenomenon really exsits. Second, the freeze-out density determines the temperature where the critical point is reached in this model. The critical point takes place at 4.25 MeV for freeze-out density 0.18 ρ_0, 5.5 MeV for 0.38 ρ_0, and 6.5 MeV for 0.60 ρ_0, respectively. Obviously, the higher the freeze-out density, the higher the critical temperature. In this case, the critical behavior is determined by the two variables, namely temperature T and freeze-out density ρ_f as observed in Pan and Das Gupta [7]. But the extraction of T and ρ_f is difficulty in view of experiments. On one side, the different thermometers give different apparant temperatures [14,15]. On other side, the freeze-out density is not directly measurable quantity in experiments. Moreover, the different initial conditions of models maybe result in different freeze-out density during the confrontations of model calculations with experimental data. All these facts complicate the accurate determination on temperature and freeze-out density and interfer with the correct extraction of physics. So it is interesting to search other variables to locate the critical phenomenon. A natural ideal is to adopt the excitation energy per nucleon E^*/A, which can be deduced or reconstructed from the experiments, especially in 4π detector measurements [15]. In the lattice gas model it can be defined as $E^*/A = E_T - E_{g.s.} = \frac{3}{2}T + \epsilon_{n,p}\frac{N_{n,p}^T}{A} - \epsilon_{n,p}\frac{N_{n,p}^{g.s.}}{A}$, where $N_{n,p}^T$ and $N_{n,p}^{g.s.}$ is the number of the bonds of unlike nucleons at T and in the ground state, respectively. In a pure classical model the ground state corresponds to a cold nucleus at zero temperature and normal nuclear density where there is no kinetic energy and so that the ground state energy per nucleon is $-\epsilon_{n,p}\frac{N_{n,p}^{g.s.}}{A}$. Practically, $N_{n,p}^{g.s.}$ is determined by the geometry and is equal to the maximum bond number of unlike nucleons possible for ^{129}Xe. The Fig.1e shows the excitation energy per nucleon E^*/A in different temperature and freeze-out density. Noted that the curves of excitation energy are not linear with temperature. If performing the differentials for these curves, we can obtain an important thermodymical quantity: the specific heat per nucleon at constant volume (or density) as $C_v/A = \frac{\partial(E^*/A)}{\partial T}$. The Fig.1f shows C_v/A as a function of T for the disassembling system ^{129}Xe at three ρ_f. Clearly, the peaks of C_v/A exist for the systems at each ρ_f and locate closely at theirself critical temperatures, which supports strongly the viewpoint about critical feature as said above. By the mapping from E^*/A to T, we replot the τ, $< IMF >$, H, and $S2$ as a function of excitation energy instead of temperature in the right column of Fig.1. Now nearly all the critical points locate at the same excitation energy regardless of the freeze-out density. Hence the excitation energy can be viewed as a more basic quantity in controlling the reaction dissociation.

In order to illustrate this point further, Fig.2 gives the average mass of the largest fragment (A_{max}), the isotopic ratio R(p/d) between protons and deutrons, the isobaric ratio R(t/^3He) between tritons and helium-3 and the ratio R(n/p) of emitted neutrons to protons as a function of temperature or excitation energy, respectively, in different freeze-out density. Again, the discrepancies stemming from different freeze-out density minimize when the excitation energy is used as the variable, and the curves for different ρ_f merge approximately into a single line.

To summarize, we studied the critical feature of Xe system and found that the critical temperature where the phase transition occurs changes with the freeze-out density which complicates the confrontation the theoretical predication with the experimental results. Contrary, we found that a unique critical excitation energy and the same excitation energy dependence of other physical observables reveals regardless of the freeze-out density, which indicates that the excitation energy can be viewed as a basic parameter to control the dissociation of the nuclear system. Unlike the temperature and freeze-out density, the excitation energy can be well extracted from experiments, especially for experiments using 4π multidetectors nowadays. Hence the use of excitation energy as a basic parameter will make it easier and definite to extract physics from the direct comparison between the experimental data and the theoretical calculation.

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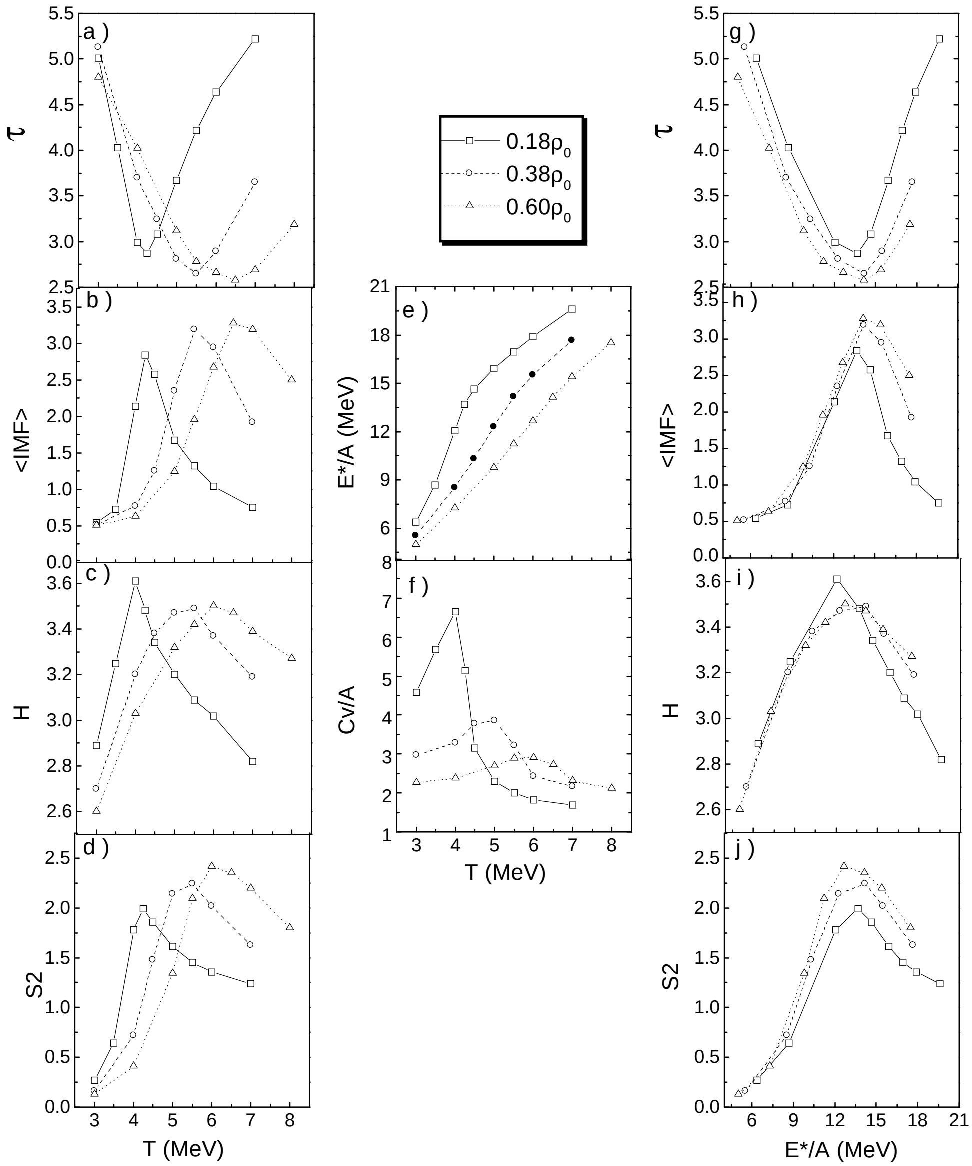
[1] G. Bizard et al., Phys. Lett. B302 (1993) 162; A. Schüttauf et al., Nucl. Phys. A607 (1996) 457.
[2] M.F. Rivet et al., Phys. Lett. B388 (1996) 219; B. Borderie et al., Phys. Lett. B388 (1996) 24.
[3] D.H.E. Gross et al., Rep. Prog. Phys. 53 (1990) 605 and references therein.
[4] J. Pochodzalla et al., Phys. Rev. Lett. 75 (1995) 1040.
[5] J.P. Bondorf et al., Phys. Rev. C58 (1998) R27.
[6] M.L. Gilkes et al., Phys. Rev. Lett. 73 (1994) 1590; J.A. Hauger et al., Phys. Rev. Lett. 77 (1996) 235. J.B. Elliot et al., Phys. Lett. B381 (1996) 35.
[7] J. Pan and S. Das Gupta, Phys. Lett. B344 (1995) 29; Phys. Rev. C51 (1995) 1384.
[8] S. Ray, J. Shamanna and T.T.S. Kuo, Phys. Lett. B392 (1997) 7.
[9] F. Gulminelli and P. Chomaz, Preprint Lpcc 98-05.
[10] X. Campi et al., Phys. Lett. 208 (1988) 351.
[11] Y.G. Ma et al., Phys. Rev. C51 (1995) 710.
[12] Y.G. Ma et al., Chin. Phys. Lett. (accepted).
[13] K.G. Denbigh and J.S. Denbigh, Entropy in Relation to Uncomplete Knowledge, Cambridge University Press, 1985.
[14] D.J. Morrissey et al., Annu. Rev. Nucl. Part. Sci. 44 (1993) 676 and references therein.
[15] Y.G. Ma et al., Phys. Lett. B 390 (1997) 41.

Figure Captions

Fig.1: The observables as a function of temperature (the left columu) or excitation energy (the right columu) in different freeze-out density: the τ parameter from the power law fit to mass distribution (a,g), the average multiplicity of intermediate mass fragments $< IMF >$ (b,h), the information entropy H (c,i) and the second moment S2 (d,j). The mapping from temperature to excitation energy is plotted in Fig.1e and the specific heat is shown in Fig.1f.

Fig.2: The average mass of the largest fragment in each event A_{max} (a,e), the isotopic ratio R(p/d) between the protons and deutrons (b,f), the isobaric ratio R(t/^3He) between the tritons and the Helium-3 (c,g), and the ratio R(n/p) of neutrons and protons (d,h). The left columu is ploted versus the temperature T and the right columu versus the excitation energy.



a)
b)
c)
d)
e)
f)
g)
h)
i)
j)
τ
<IMF>
H
S2
E*/A (MeV)
Cv/A
T (MeV)
$0.18\rho_0$
$0.38\rho_0$
$0.60\rho_0$

Fig. 1

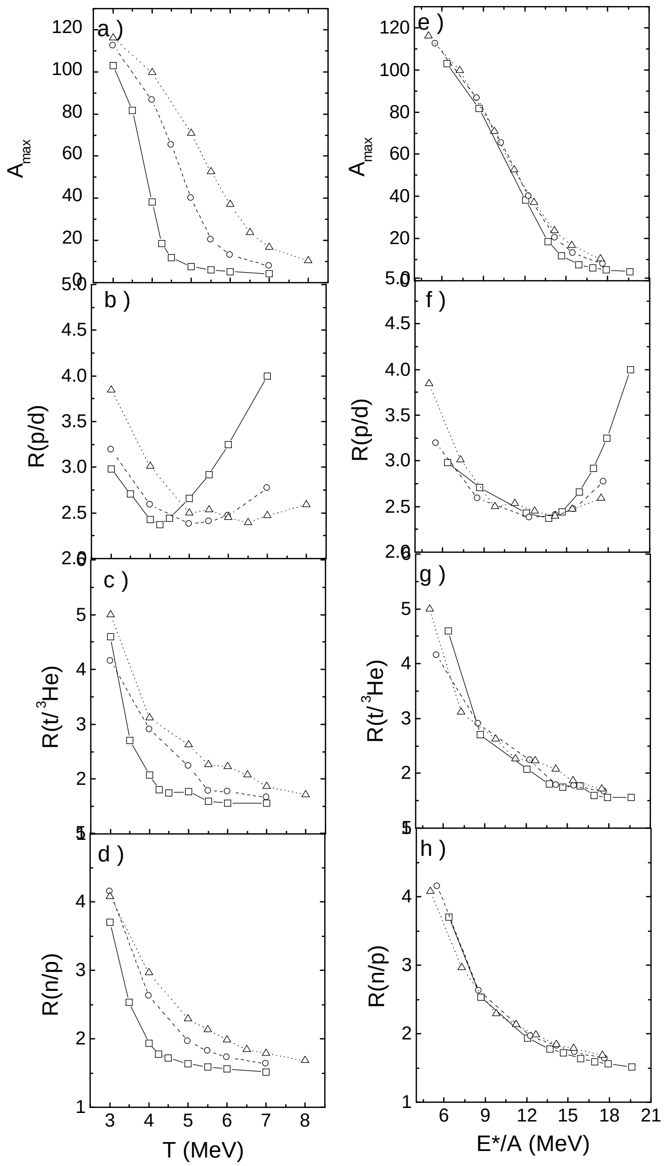


Fig.2